Cutting Processes I

Reading assignment:

- 20.1 – 20.3, 20.5

Cutting processes I

Cutting processes

- Process planning, Cost, Quality, Rate and Flexibility

Modeling: Orthogonal cutting

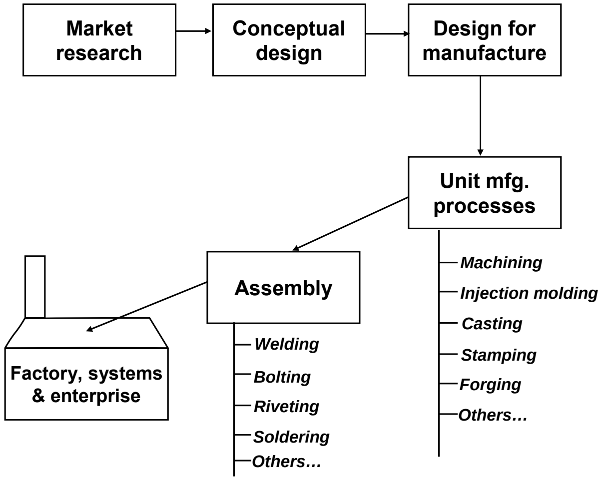
- Video, geometry, forces and power

Demonstration

Cutting equipment/tools

Design for Manufacturing: Cutting

Process variation



Market research
Conceptual design
Design for manufacture
Unit mfg. processes
Machining
Injection molding
Casting
Stamping
Forging
Others…
Assembly
Welding
Bolting
Riveting
Soldering
Others…
Factory, systems & enterprise

Material removal processes

Mechanical removal processes

- Milling Turning Shaping
- Grinding Broaching

Others

- Thermal Electrochemical Chemical

In general:

<u>Cost</u>	<u>Flexibility</u>	<u>Quality</u>	<u>Rate</u>
Expensive	Complex shapes	Depends	Slow

Understanding what is going on

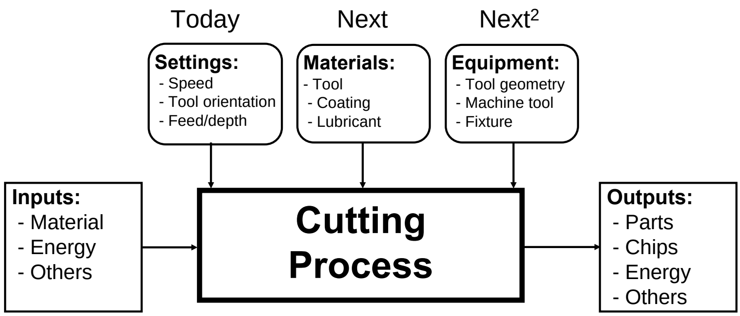
Key issues

- ⊙ **How does cutting work?**
- ⊙ **Linking the Cost, Flexibility, Quality and Rate to process parameters**

Available methods to design process parameters:

- ⊙ **Analytic** **Numerical** **Experimental**

Process planning & cutting process



Today Next Next^2

Settings:
- Speed
- Tool orientation
- Feed/depth

Materials:
- Tool
- Coating
- Lubricant

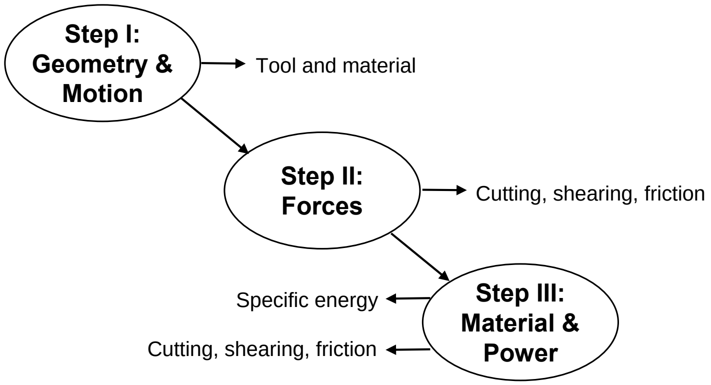
Equipment:
- Tool geometry
- Machine tool
- Fixture

Inputs:
- Material
- Energy
- Others

Cutting Process

Outputs:
- Parts
- Chips
- Energy
- Others

Steps we will take to get there



Step I: Geometry & Motion → Tool and material

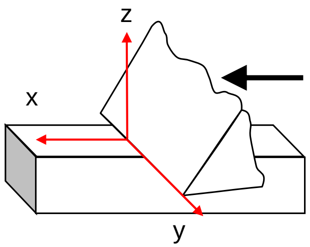
Step II: Forces → Cutting, shearing, friction

Step III: Material & Power → Specific energy

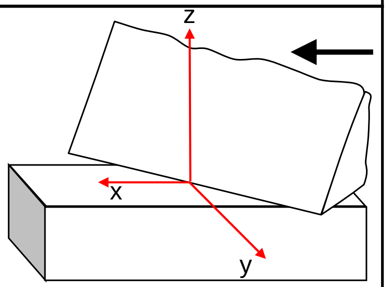
Step III: Material & Power → Cutting, shearing, friction

Geometry & Motion → Forces → Material & Energy/Power

Basic cutting geometries



Orthogonal (2D)



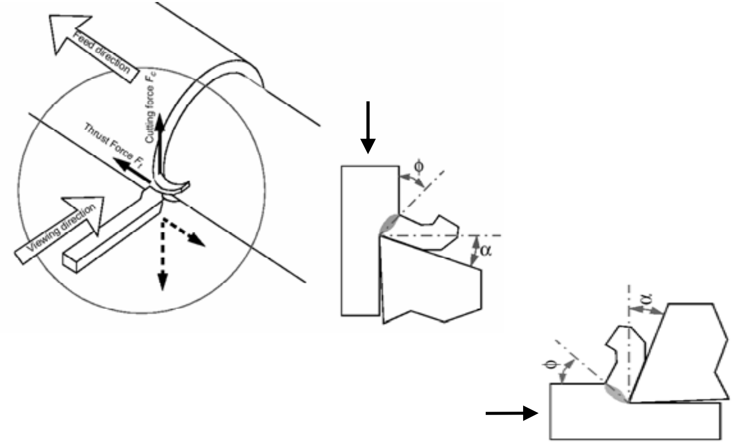
Oblique (3D)

Orthogonal → Provides insight for understanding

Oblique → Complex, diminishing returns

Geometry & Motion → Forces → Material & Energy/Power

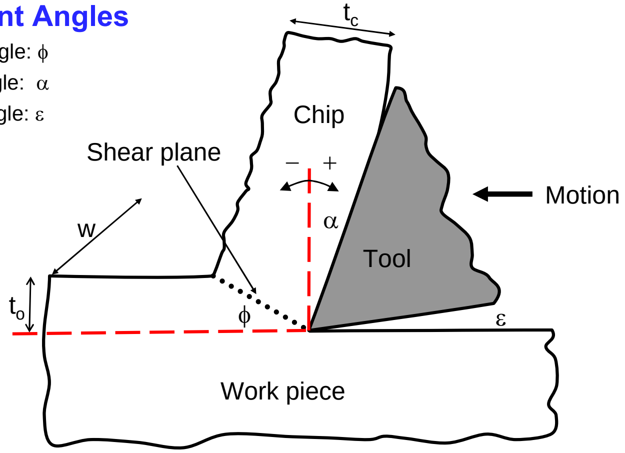
Orthogonal cutting in a lathe



Orthogonal cutting zone geometry

Important Angles

- Shear angle: ϕ
- Rake angle: α
- Relief angle: ε



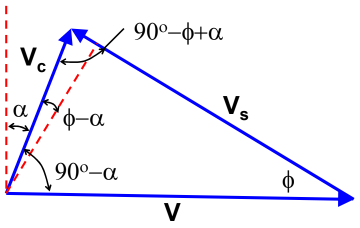
CUTTING VIDEO

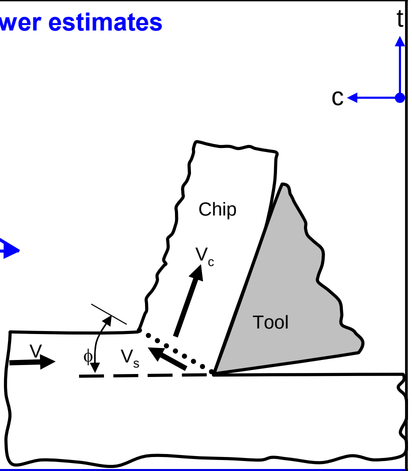
Key issue:

- ⊙Motion and material flow
- ⊙Types of chips
- ⊙How chip type relates to material

Velocity diagram of cutting zone

Need velocities to obtain power estimates





$$\frac{V}{\sin\left(\frac{\pi}{2}-\phi+\alpha\right)}=\frac{V_s}{\sin\left(\frac{\pi}{2}-\alpha\right)}=\frac{V_c}{\sin(\phi)}$$

$$\frac{V}{\cos(\phi-\alpha)}=\frac{V_s}{\cos(\alpha)}=\frac{V_c}{\sin(\phi)}$$

Cutting ratio, r

From mass conservation:

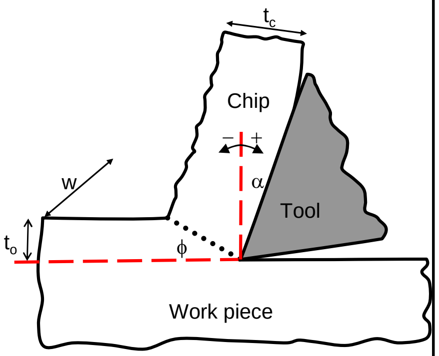
$$\rho \cdot t_o \cdot w \cdot V = \rho \cdot t_c \cdot w \cdot V_c$$

From velocity diagram:

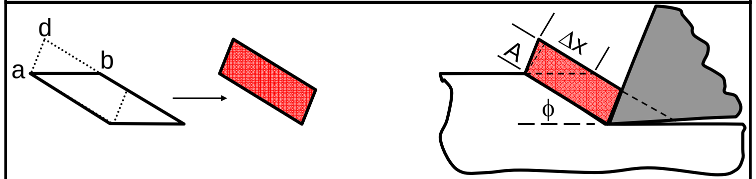
$$\frac{V}{\cos(\phi-\alpha)} = \frac{V_c}{\sin(\phi)}$$

Cutting ratio:

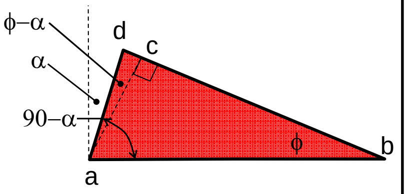
$$\frac{V_c}{V} = \frac{t_o}{t_c} = r = \frac{\sin(\phi)}{\cos(\phi-\alpha)}$$



Analysis of shear strain



$$\gamma = \frac{\Delta x}{A} = \frac{bc+cd}{ac} = \cot(\phi) + \tan(\phi-\alpha)$$



What does this mean:

- ⊙ φ↓ = γ↑

Cutting forces and power

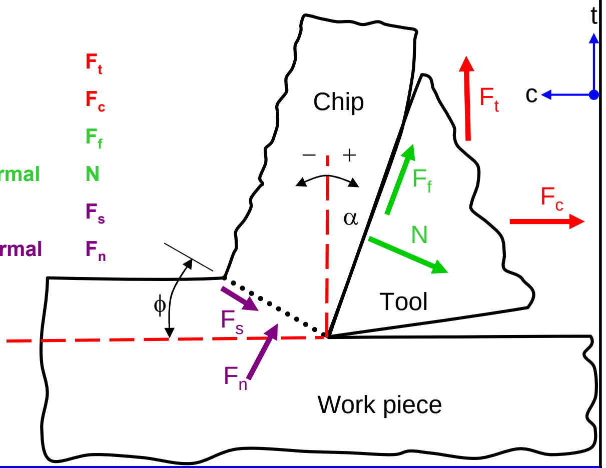
Why do we need to know the cutting force/power?

- ⊙ Designing parts / machine tools (power and stiffness)
- ⊙ Part, machine and tool deflection
- ⊙ Trade offs in process planning, CFQR…
- ⊙ Equipment suitability
- ⊙ Others….

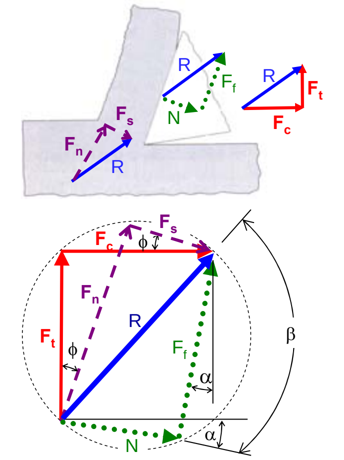
Cutting forces

Forces:

⊙ **Thrust**	F_t
⊙ **Cutting**	F_c
⊙ **Friction**	F_f
⊙ **Tool normal**	N
⊙ **Shear**	F_s
⊙ **Chip normal**	F_n



Merchant’s diagram: Force relationships



Shear plane forces:

$$F_s = F_c \cdot \cos(\phi) - F_t \cdot \sin(\phi)$$

$$F_n = F_c \cdot \sin(\phi) + F_t \cdot \cos(\phi)$$

Tool-chip forces:

$$F_f = F_c \cdot \sin(\alpha) + F_t \cdot \cos(\alpha)$$

$$N = F_c \cdot \cos(\alpha) - F_t \cdot \sin(\alpha)$$

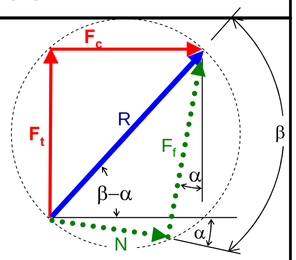
$$\mu = \frac{F_f}{N} = \tan(\beta)$$

$$Typcially: 0.5 < \mu < 2$$

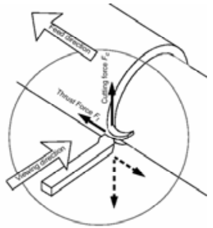
Cutting and thrust forces

$F_t = F_c \tan(\beta - \alpha)$

- ⊙ $\beta < \alpha$ tool is pulled into part
- ⊙ $\beta > \alpha$ tool is pushed away
- ⊙ $\beta = \alpha$ no thrust force



Use high α for thin cuts?

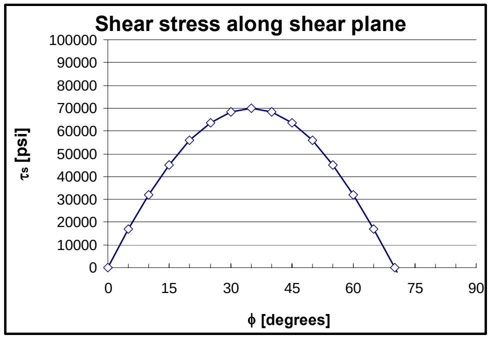


ϕ and τ_s

Magnitude of shear stress varies with angle of shear plane

$$\tau_s = \frac{F_s}{A_s} = \frac{F_c \cdot \cos(\phi) - F_t \cdot \sin(\phi)}{\left[t_o / \sin(\phi)\right] \cdot w}$$

ϕmax	35	degrees
	0.61	radians
Fc	**225**	lbf
α	**20**	degrees
	0.35	radians
β	**40**	degrees
	0.70	radians
to	**0.015**	inches
w	**0.075**	inches
τs	70021	psi



Merchant’s relationship

Merchant’s assumption:

- ⊙ Shear angle adjusts to maximize τ_s

$$\tau_s = \frac{F_s}{A_s} = \frac{F_c \cdot \cos(\phi) - F_t \cdot \sin(\phi)}{\left[t_o / \sin(\phi)\right] \cdot w} \qquad \frac{F_t}{F_c} = \tan(\beta - \alpha)$$

$$\downarrow$$

$$\frac{d\tau_s}{d\phi} = \frac{F_c}{t_o \cdot w}\left[\cos^2(\phi) - \sin^2(\phi) - \frac{F_t}{F_c} \cdot 2 \cdot \sin(\phi) \cdot \cos(\phi)\right] = \frac{F_c}{t_o \cdot w}\left[\cos(2\phi) - \frac{F_t}{F_c} \cdot \sin(2\phi)\right]$$

$$\frac{d\tau_s}{d\phi} = 0 \rightarrow \left[\frac{\cos(2\phi)}{\sin(2\phi)} - \frac{F_t}{F_c}\right] = 0 = \frac{\cos(2\phi)}{\sin(2\phi)} - \frac{\sin(\beta - \alpha)}{\cos(\beta - \alpha)}$$

$$\cos(2\phi) \cdot \cos(\beta - \alpha) - \sin(2\phi) \cdot \sin(\beta - \alpha) = 0 = \cos(2\phi + \beta - \alpha)$$

$$\boxed{2\phi + \beta - \alpha = \frac{\pi}{2} \rightarrow \phi = \frac{\pi}{4} - \frac{\beta}{2} + \frac{\alpha}{2} \longrightarrow \text{Merchant’s relationship [radians]}}$$

The use of Merchant's relationship

$$\phi = \frac{\pi}{4} - \frac{\beta}{2} + \frac{\alpha}{2}$$ ⟵ Merchant's relationship [radians]

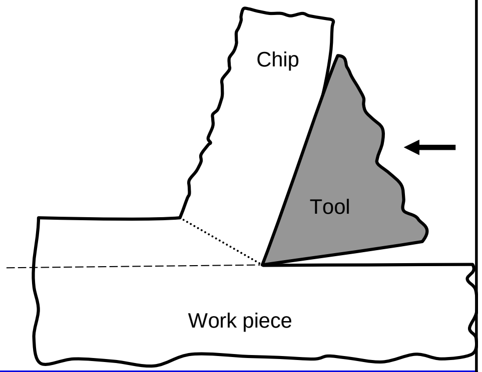
As rake angle ↓ or as friction angle ↑

- **Shear angle ↓**
- **Chip thickness ↑**
- **Energy dissipation via shear ↑**
- **Heat generation ↑**
- **Temperature ↑**

Power/energy requirements

What happens to energy you put in?

- **Shear**
- **Friction**
- **Others?**



Specific energy (table from Kalpajkian)

$$u_s = \left.\frac{\text{Energy}}{\text{Volume}}\right|_{\text{certain conditions}}$$

Approximate Energy Requirements in Cutting Operations	
Assumed for 80 % motor efficiency	
	J / mm^3
Aluminum alloys	0.40 – 1.10
Copper alloys	1.40 – 3.30
Cast irons	1.60 – 5.50
Steels	2.70 – 9.30
Stainless steels	3.00 – 5.20

Power and specific energy

Specific energies to consider:

Shear +	Friction +	Others =	Total
$u_s = \frac{F_s \cdot V_s}{w \cdot t_o \cdot V}$	$u_f = \frac{F_f \cdot V_c}{w \cdot t_o \cdot V}$	*Others*	$u_t = \frac{F_c \cdot V}{w \cdot t_o \cdot V}$
$u_s = \frac{\tau_s}{\sin(\phi)} \cdot \frac{V_s}{V}$			
$u_s = \tau_s \cdot \gamma$			
~75%	~20%	~5%	100%

Cutting Processes II

Reading assignment:

- 20.6 – 20.8
- 21.1 – 21.6, 21.13

Cutting processes II

Cutting processes

- Process planning, Cost, Quality, Rate and Flexibility

Modeling: Orthogonal Cutting

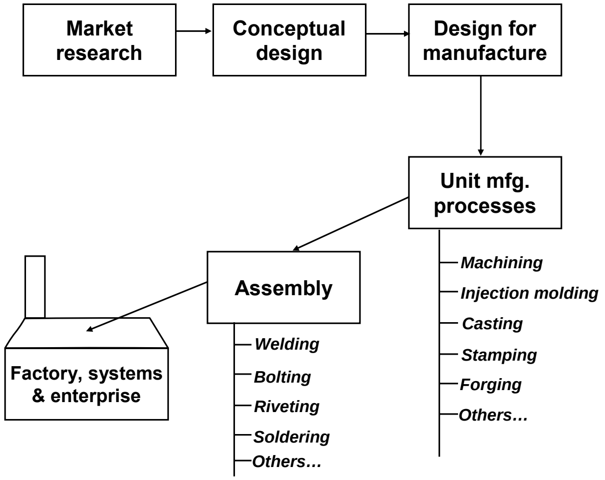
- Video, geometry, forces and power

Demonstration

Equipment and tools

Design for Manufacturing

Process variation

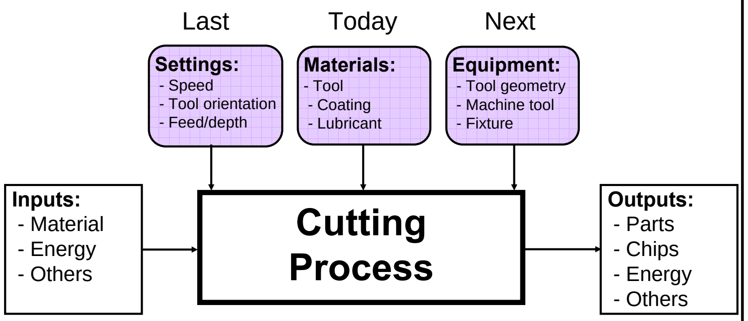


Market research → Conceptual design → Design for manufacture → Unit mfg. processes → Assembly → Factory, systems & enterprise

Unit mfg. processes:
- *Machining*
- *Injection molding*
- *Casting*
- *Stamping*
- *Forging*
- *Others…*

Assembly:
- *Welding*
- *Bolting*
- *Riveting*
- *Soldering*
- *Others…*

Process planning & cutting process



Last	Today	Next
Settings: - Speed - Tool orientation - Feed/depth	**Materials:** - Tool - Coating - Lubricant	**Equipment:** - Tool geometry - Machine tool - Fixture

Inputs:
- Material
- Energy
- Others

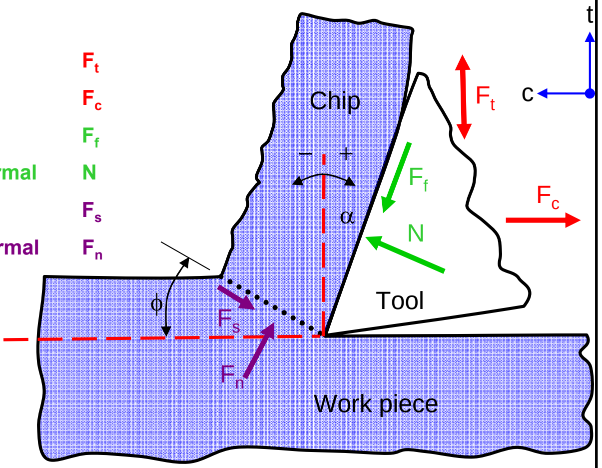
→ **Cutting Process** →

Outputs:
- Parts
- Chips
- Energy
- Others

Review: Cutting forces

Forces:

⊙ **Thrust**	**F_t**
⊙ **Cutting**	**F_c**
⊙ **Friction**	**F_f**
⊙ **Tool normal**	**N**
⊙ **Shear**	**F_s**
⊙ **Chip normal**	**F_n**



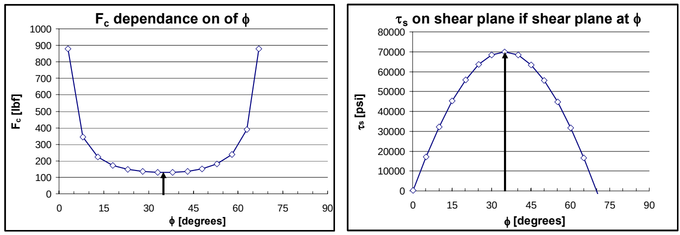
Merchant’s minimum energy assumption

Assumption: φ adjusts to value that minimizes cutting energy

- ⊙ **If Energy need to cut is minimized, F_c is minimized for a given V**

$$\frac{\partial}{\partial t}\underset{\boxed{\text{Minimize}}}{(E_{cut})} = \underset{\boxed{\text{Minimized}}}{P_{cut}} = \underset{\boxed{\text{Minimized}}}{F_c} \cdot \underset{\boxed{\text{Constant}}}{V}$$

- ⊙ **F_c is minimum when shear plane is plane of maximum shear stress**
- ⊙ **Example: F_c = minimum and τ_s = maximum for $\phi = 35^o$ (for same α and β)**



Merchant’s relationship

Merchant’s relationship:

- ⊙ $\phi = \frac{\pi}{4} - \frac{\beta}{2} + \frac{\alpha}{2}$
- ⊙ **It is an idealization, not always accurate, BUT the trend is consistent**

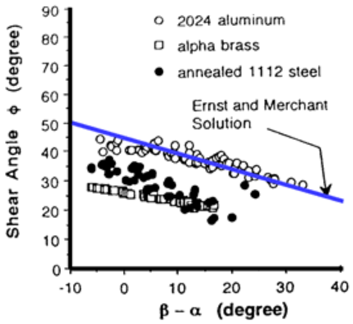


Chart adapted from: Metal Cutting Theory and Practice, Stephenson and Agapiou

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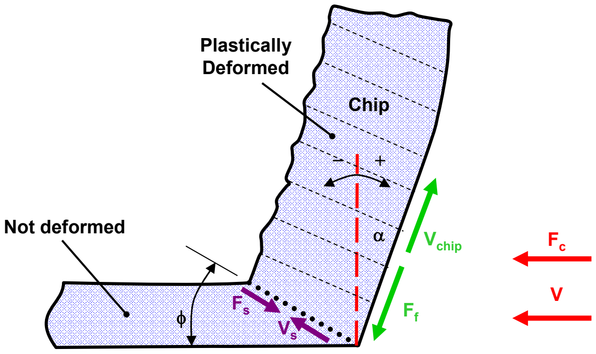
Review: Power and specific energy

Specific energies to consider:

Shear energy +	Friction energy +	Others	=	Total energy
$u_s = \frac{F_s \cdot V_s}{w \cdot t_o \cdot V}$ $u_s = \frac{\tau_s}{\sin(\phi)} \cdot \frac{V_s}{V}$ $u_s = \tau_s \cdot \gamma$	$u_f = \frac{F_f \cdot V_c}{w \cdot t_o \cdot V}$	*Others*		$u_t = \frac{F_c \cdot V}{w \cdot t_o \cdot V}$
~75%	~20%	~5%		100%



Caution on modeling and reality

Our assumptions:

- Slow, orthogonal cutting
- Material properties invariant
- Constant temperature
- Simple sliding friction
- No strain hardening

Use our analysis for:

- Trends & building intuition
- Basis for detailed study

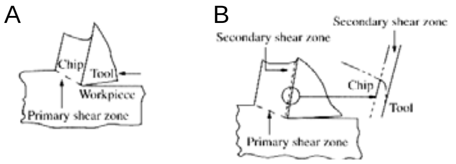
Chip types (source: Kalpajkian)

A) Continuous chip with narrow primary shear zone

- Ductile materials @ high speed
- Bad for automation (use chip breakers)

B) Secondary shear zone at chip-tool interface

- Secondary shear zone -> increased energy dissipation



Source: Kalpajkian

Chip types (source: Kalpajkian)

D) Continuous chip with build up edge (BUE)

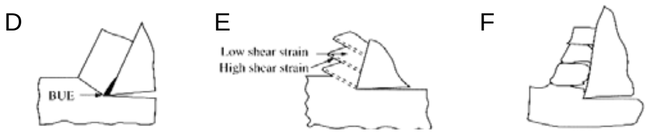
- High plastic working and bad for automation

E) Serrated chip:

- Low thermal conductivity materials

F) Discontinuous chip (good chips)

- Low ductility materials and/or negative rake angles



Source: Kalpajkian

CUTTING DEMONSTRATION

Example

Given:

- t_o w ω P_{lathe}

Find:

- Velocity at which lathe stalls
- Cutting force

TOOL MATERIALS AND TOOL WEAR

Cutting tool requirements

Maintain:

- Hardness at operating temperature
- Toughness
- Low wear rate

Should be easy to repair/sharpen

Tool-part combination should be chemically inert

- Diamond and steel….

Cutting tool characteristics

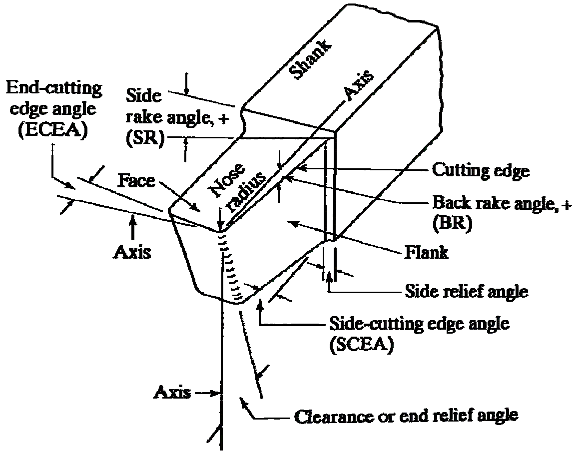
Why do we worry about tool wear?

- Tool can cease to cut   Dimensional accuracy
- Surface finish   Cutting force/power
- Cost   Flexibility   Rate   Quality

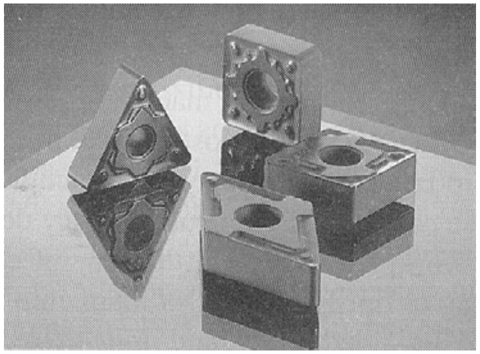
Is a function of many parameters

- Coolant   Geometry   Lubricant   Process parameters

Cutting tools: Geometry



Cutting tools: Geometry

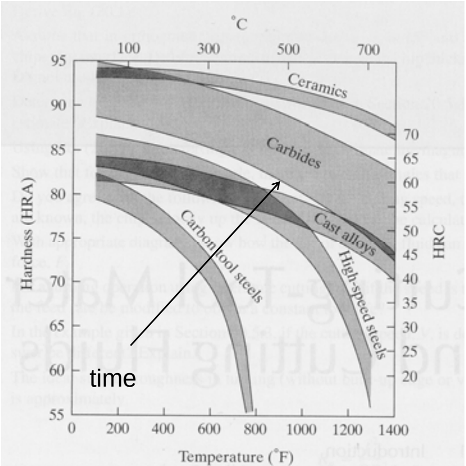


Source: Kalpajkian

Tooling hardness and temperature

Things to note:

- Performance ↑
- Rate of change ↓

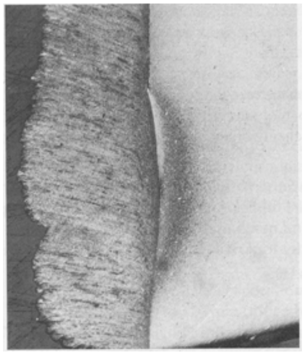


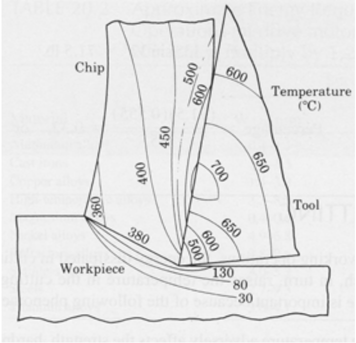
Source: Kalpajkian

Temperature and wear

Diffusion is thought to dominate crater wear

This is a function of temperature





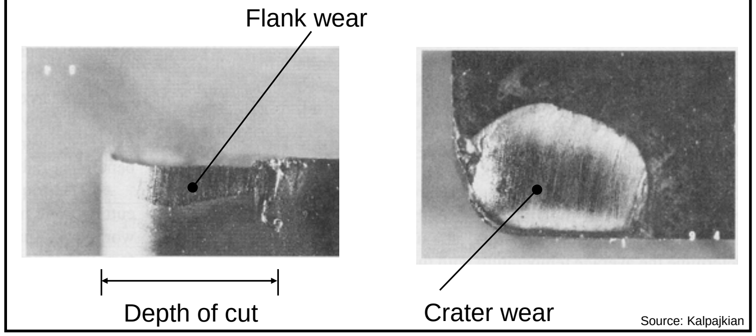
Source: Kalpajkian

Tool wear up close

Crater wear affected by same parameters as flank wear

In addition:

- **Material affinity and temperature**

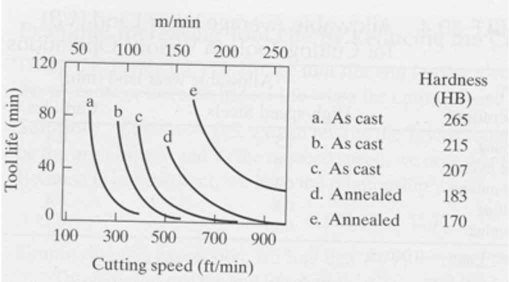


Source: Kalpajkian

Taylor's wear relationship (flank wear)

Relationship between tool life and cutting speed

- **Use to set optimum cutting speed for CFRQ**
- **Represents a given wear condition**
- **Define wear condition for failure**



Source: Kalpajkian

Defining tool failure

Wear "snowballs" to set limit

Force/power increase to set limit

Surface finish becomes unacceptable

Wear land size for given process

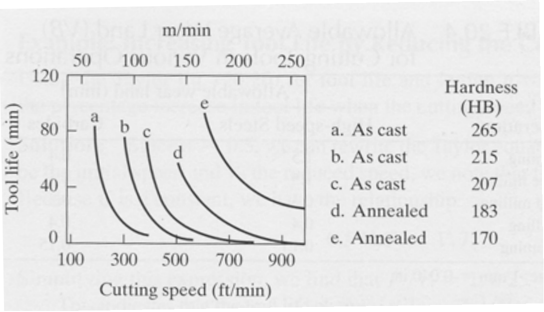
Taylor's wear relationship (flank wear)

C = constant & n = exponent (from experimental data)

$$v \cdot t^{n} = C$$

v = cutting velocity (fpm)

t = time to failure (min)



Source: Kalpajkian

Taylor's tool life curves (Experimental)

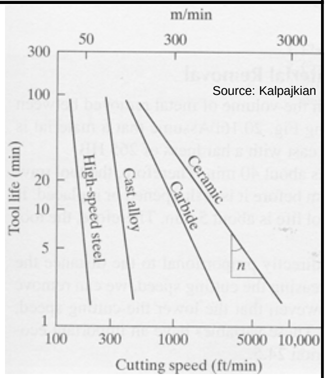
Coefficient n varies from:

Steels	**Ceramics**
0.1	0.7

$$v \cdot t^{n} = C$$

v = cutting velocity (fpm)

t = time to failure (min)



Source: Kalpajkian

As n ↑, wear is less sensitive to cutting speed

Preventing tool failure with coatings

Tools may be coated for many reasons:

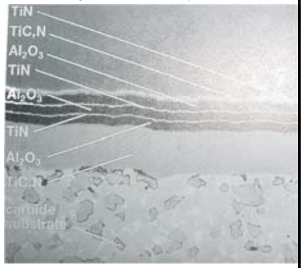
- **Chemically inert**
- **Temperature resistance**
- **Surface energy/specific energy**
- **Low friction**

Common coatings

- **Titanium nitride (TiN)**
- **Cubic boron nitride (cBN)**
- **Multi-phase coatings**

Multi-phase coating

Layers ½ – 10 μm thick



CUTTING PROCESS DFM

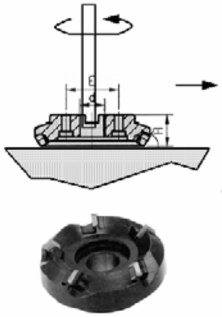
DFM for cutting: Surface roughness

Surface roughness:

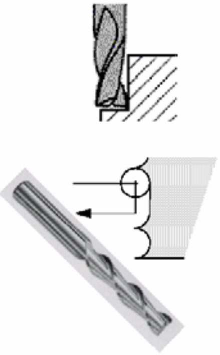
- Definition

Depends on :

- Mass removed
- Size of tool
- Cutter
- Speed

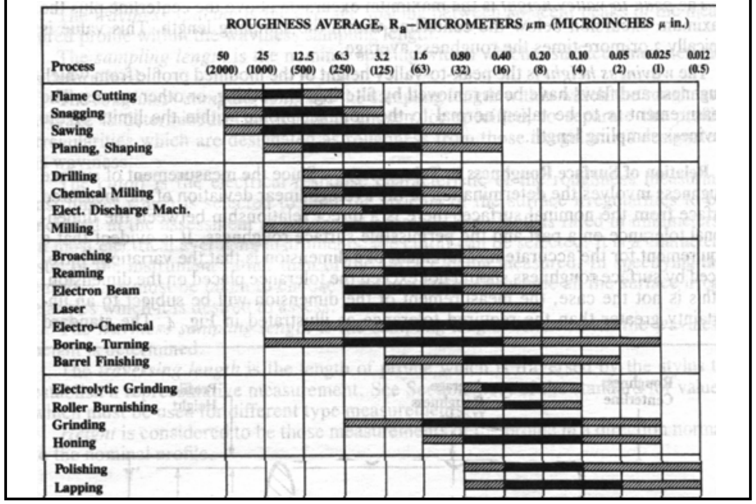


A face milling operation will render a smooth finish



Side milling with an end-mill will give you some surface roughness.

Finish by process (source = machinery handbook)

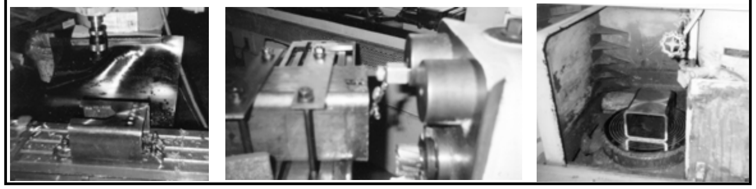


DFM for cutting: Part geometry

Thin sections and tubes (vibration)

Overhanging parts

Inclined planes and drilling….



DFM for cutting: Ala features

Use common dimensions / parts / shapes / sizes

- Proper tolerance
- Use common/important datums
- Standard features (i.e. don’t use octagon shaped holes)

DFM for cutting: Ala tooling

Avoid deep pockets and holes

Design should include real shape tool makes

- Tapped holes
- Pocket corners

DFM for cutting: Ala equipment

Beware of fixturing needs

- Minimize number of fixture cycles
- Design an interface for part-fixture

Machine and tool access to create features